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Lines of Energy Deposition for Supersonic/Hypersonic Temperature/Drag-Reduction and Vehicle Control

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Abstract. Lines of energy are deposited ahead of supersonic and hypersonic vehicles in order to create a low-density channel, through which a vehicle can travel with dramatically reduced drag. Temperature and pressure are both also reduced on the front surfaces of the vehicle, while density and pressure are increased at the vehicle base. When applied off-center, this technique can be used to control the vehicle, employing the entire body as the control surface and eliminating the need for actuators. Results for drag-reduction, temperature-reduction, and control forces are presented here.

Keywords: Laser Guided Electric Discharge; Supersonic; Hypersonic; Drag Reduction; Temperature Reduction; Vehicle Control; Shock Wave; Shock Mitigation; Energy Deposition; Gas Heating.
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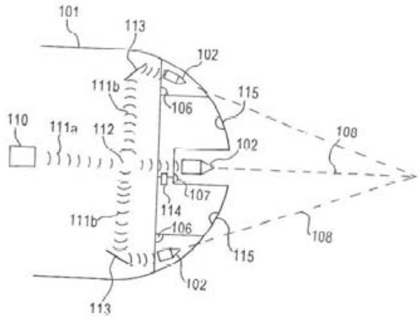
HYPERSONIC DRAG REDUCTION AND CONTROL

Applications and Background

Hypersonic and supersonic vehicles/missiles generate shock waves, which are accompanied by a host of technical challenges. These include increased drag, sonic boom, and destructively high temperatures and pressures on their airframe and components. "Suddenly heating" an extended path of air, ahead of the shock wave and along the vehicle's velocity vector, results in rapid expansion of the heated air. This creates a long, hot, low-density core, into which the vehicle's shock wave expands, followed by the vehicle itself (Figure 1c). This deposition occurs in pulsed fashion, being repeated when each core has been traversed and the ambient air is once again encountered by the vehicle. Strategically heating extended regions of gas ahead of the vehicle can therefore mitigate the shock wave, as well as its deleterious effects. Also, since the vehicle will preferentially fly along the low-density channel, (e.g. be partially steered by it), adjusting the direction/position of the hot core formation can be utilized as a method of control (Figure 2).



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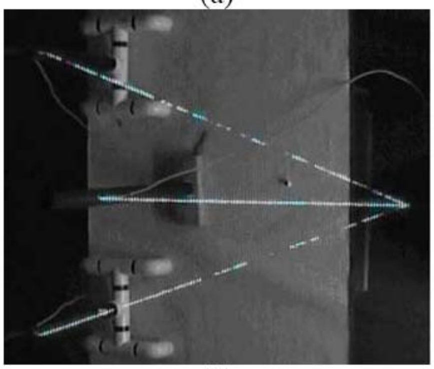

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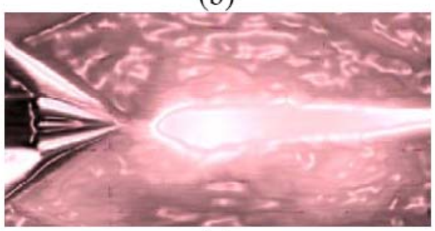
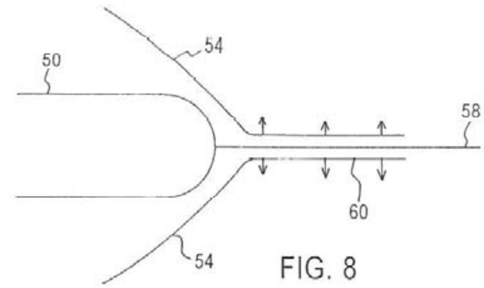
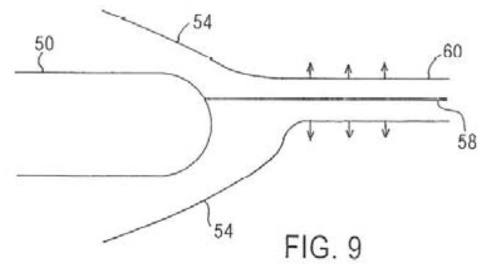


(c)

FIGURE 1: (a) Generation of three lines to complete a symmetrical electric circuit. (b) Electric discharges in this same geometry. Note the greater strength along the single central return path than along the two outside paths. (c) Strong energy disposition in a supersonic wind tunnel. [2, 3, 4]





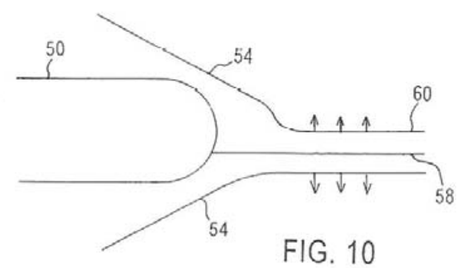


FIGURE 2: Air is heated off-axis to generate asymmetric drag-reduction, thereby facilitating control. [5, 6, 7]

The full range of supersonic/hypersonic systems/applications (both civilian and military) can benefit from this technology, including, including space launch and atmospheric re-entry, sub-vehicle separation, and with less dramatic effects for subsonic/transonic flight [5,6,7].

In addition to drag reduction and flow control, effective shock wave mitigation will also decrease ablation/heat-resistance (TPS) requirements of critical surfaces and components. The potential result is therefore faster, lighter, more durable/maneuverable systems, with increased kinematic footprints. Our calculations and simulations demonstrate a reduction in wave drag of up to 82% for a 15° half-angle cone and up to 96% for a 45° half-angle cone. The energy return ratio [thrust (power) saved]:[invested power] of this technique increases with Mach number, and is much higher than for point-wise energy-deposition. The improvement in efficiency is

a direct result of the linear/cylindrical geometry, which effectively uses all of the deposited energy to move air laterally out of the vehicle's path [2,3,4]. The linear geometry also allows the use of electric discharges to deposit energy, which are far more efficiently generated than laser pulses, and which couple their energy more efficiently into the flow. The electromagnetic aspect of this technology addresses the

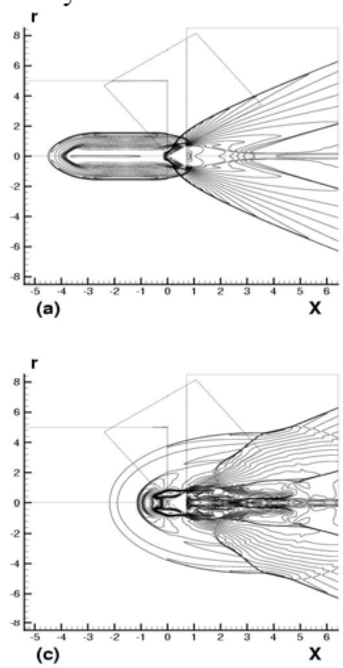


FIGURE 3: A low-density core streaming over the cone. (Mach 2) [1]

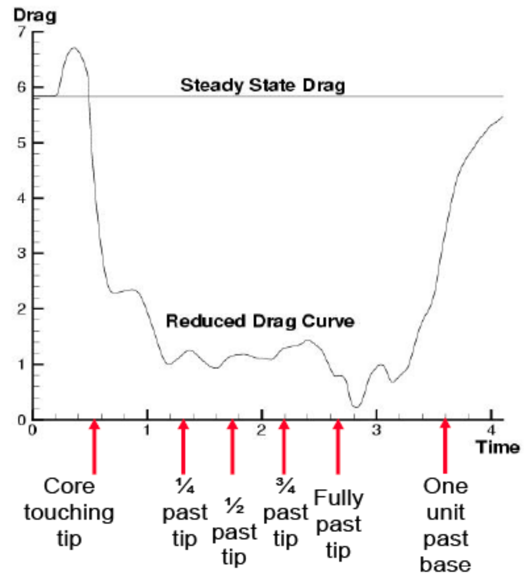


FIGURE 4: Significant drag reduction, as the low-density core streams over the cone (Mach 2). [1]

desire to move away from mechanical actuator systems and control surfaces. The technology's notable ability to "streamline" and control arbitrary bodies/shapes furthermore addresses the desire to reduce the time and cost of design, development, manufacturing, and maintenance. This will allow manufacturers to approach the ideal situation of designing an airframe around its payload and mission, while relying on an electromagnetic system to do the "stream-lining" for them. A long, hot path, opened up ahead of an airframe (Figure 3), can be considered to provide any vehicle with a much more favorable "effective aspect ratio", yielding a much higher L/D (lift-to-drag ratio). In essence, the proposed geometry allows a vehicle to coast through the low-density tube, with greatly reduced resistance (Figure 4), and the nature of the control forces exerted on the body by the flow are to center the vehicle along the low-density, low-resistance path. Creation of such a path is described in more detail below, and the basic mechanism employs a high-intensity, low-energy laser pulse, followed by a high-energy electric discharge. The high-intensity (filamenting) laser pulse creates an ionized path in the air to complete a circuit (Figure 1a), which initiates and guides the electric discharge. The electric discharge deposits energy along its path in the air (like a lightning bolt), generating an expanding cylindrical shockwave, which pushes the air outward from the path. This leaves behind the low-density tube (Figure 3), through which the vehicle can travel with greatly-reduced drag. This low-density tube has been well characterized, both by Plooster and in our simulations [1].

The potential benefits of this program apply to all high-speed flight applications. Reducing drag translates directly into lower weight from thermal shielding and fuel, or into greater range and/or payload, while the associated reduction in heating/pressure translates into less stringent materials requirements, less damage, and/or increased performance envelopes. Reducing drag at an angle or "off-axis" steers and controls the vehicle, since it will travel along the center of the low-density tube ahead of it. This presents the alluring ability to use the vehicle's body as the only required control and lifting surface, as it balances the moments/forces to keep the vehicle confined within the low-density path. Sonic boom mitigation also reduces the environmental (acoustic) impact of high-speed vehicles, which increases their effective operating domain. The combination of all of these benefits, when applied to defensive systems, stands to increase their kinematic footprint through greater speed and range with a lower acoustic signature. In the past, air has been "pushed" laterally out of the way of a moving vehicle by using an aerospike. The approach, described here, offers the possibility of pushing air laterally out of a vehicle's way far ahead of the vehicle. This method is even more alluring, because the "pushing" is performed without the impediment of a physical spike (spikes can become a liability when the vehicle is moving at a non-optimized angle of attack). Angle of attack does not represent a limitation when using this technique, since the laser guides can be directed at arbitrary angles with respect to the vehicle.

In a targeting scenario, three additional benefits are automatically attained when using this technique:

- High-speed maneuvering/control, which becomes more effective/efficient at greater Mach numbers, allowing the opportunity to overcome the problems of supersonic/hypersonic implementation of traditional control methods, which were originally developed for subsonic flight.
- Greatly enhanced forward visibility through the low-density tube, which allows for improved imaging capabilities (and target recognition for defensive systems).
- Automatic "painting" with the filamenting laser pulse, in the direction the vehicle is being guided, allowing either object avoidance or locking/closing, depending on the nature of the vehicle/mission.

Each of the technical elements required to implement this technology has been demonstrated individually in the laboratory, with no apparent physical limitation barring execution as a full system.

Electromagnetic heating/propagation through air

The experiments we have performed to date have used ultrafast, high energy lasers, ranging in wavelength from 248-1054nm and in pulse width from 400fs-8ps. The relatively recent development in laser pulse technology, which significantly broadens our options for heating an extended path, is the filament formation shown in Figures5 and 6. The Diels Research Group has been the primary pioneer in UV filaments, which overcome/complement many of the shortcomings of using IR. Theoretical results from Schwarz and Diels [9] demonstrate an oscillatory exchange, over length

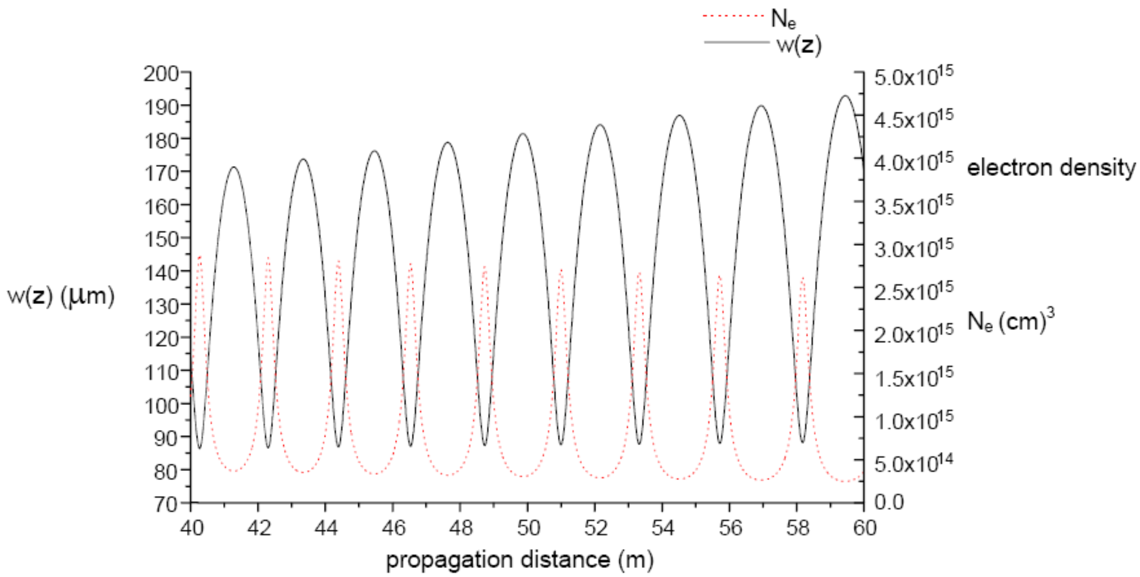


FIGURE 5: Simulation results of filament diameter and electron concentration as a function of propagated distance, for an initial power of 49.5 MW. Significant photoionization is seen only to occur over short lengths for which the beam confinement is maximum. [9]

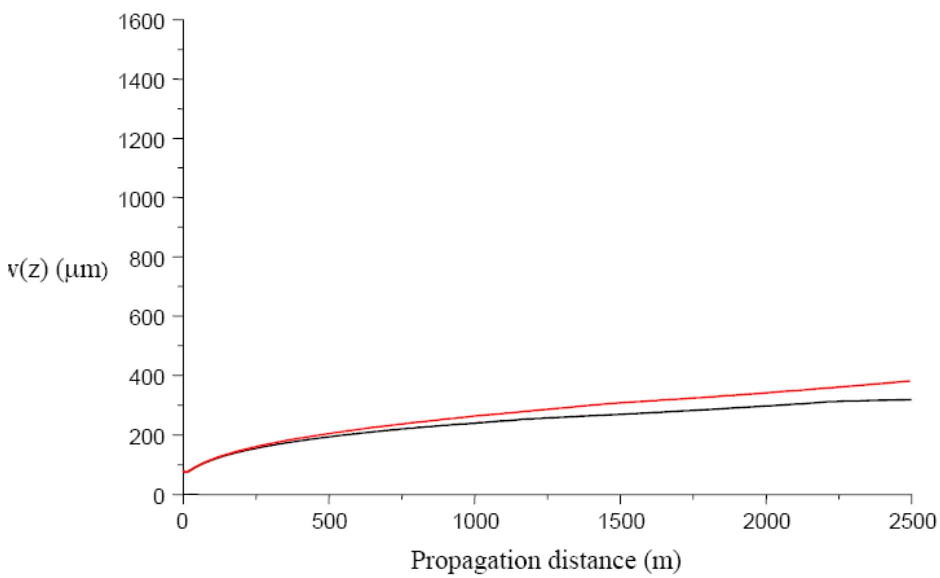
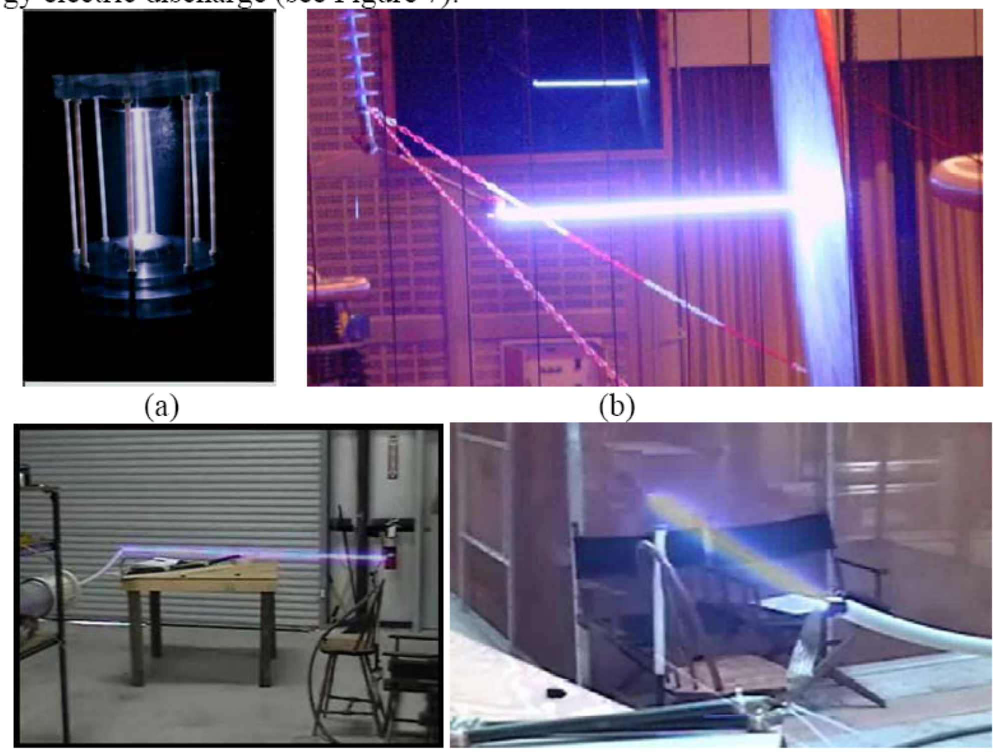


FIGURE 6: Simulation of a UV filament envelope diameter as a function of propagated distance, for an initial power of 160 MW. The filament diameter remains confined roughly within 100 microns over thousands of meters. [9]

scales of meters, between the field intensity and the ionization (Figure 5). These oscillations take place within an envelope that is predicted to extend for kilometers (Figure 6), given sufficient initial energy. Simulations show effectively zero spread of the beam, and the predictions of this model agree well with experiment.

Our proposed technology depends critically on coupling electromagnetic energy into air in a precisely defined, extended geometry ahead of a vehicle's shockwave. For our applications, we require a well-controlled extended swath of air to be heated as efficiently as possible. Using only a laser to heat the atmosphere is very expensive, due to the generally inefficient conversion of electricity to laser light. If, instead, a

weakly-ionized channel is created in the air using only milliJoules of laser energy, this channel can be used to conduct a high-energy electric discharge, which will couple energy into the air much more effectively than a laser. The energy emitted by the electric discharge is also much more cost-effectively generated than that emitted by a laser. This method of increasing both heat-deposition and efficiency uses the low-energy, laser-ionized swath of gas, not only to nucleate, but also to guide the high-energy electric discharge (see Figure 7).



(a) (b) (c) (d)

FIGURE 7: a) UV laser-guided electric discharge across 30cm [8];similar laser filament-guided discharge over 2 meters [10]; c & d) Using a pulsed discharge and surrogate filaments, discharges over 3 meters were formed.

NUMERICAL RESULTS

In implementing the weighted Essentially Non-Oscillatory (wENO) code developed by Shu and Sebastian, our first step was to compute the steady state flow initial conditions for three different cone angles and four different Mach numbers. The results compared extremely closely to analytical results with base pressure corrections, compiled from NASA wind tunnel data[1]. After this, it was necessary for us to determine the amount of energy to deposit along the cone axis in order to open up low-density cylindrical cores of various radii. The reason behind modeling the effects of different radius cores was to determine if benefit can be derived by simply opening up a small core and "puncturing the shock" to allow high pressure gas to escape...or if it is necessary to actually push the bulk of the air completely to the side.

Each of the steady state flows of Mach 2,4,6,8 for each of the cone half-angles (15, 30, 45 degrees, all with the same base radius) was subjected to an instantaneous line-

deposition of energy. Four different core radii were explored: 1/4 the base radius (0.25R); 0.5R; 0.75R; and 1.00R. As expected, the energy/length required to open a 1.00R core was 16 times the energy required to open a 0.25R core.

The long columns of energy, deposited ahead of a vehicle, significantly reduced pressures and the resulting drag forces in the supersonic and hypersonic regimes. This occurs because the expansion of the cylindrical shockwave from the line of deposited energy results in the long, low-density column of air ahead of the vehicle, as described above. This column of low-density air interacts with the vehicle's shockwave, providing a low-density channel, along which the high pressure gas in front of the vehicle can escape, and along which the vehicle can travel with greatly reduced wave drag. The commensurate reduction in heating and pressure can reduce materials requirements, and when applied off-axis, the off-center drag-reduction will generate strong steering moments. Having compared this method to energy-deposition at a "point" ahead of the shockwave, we have numerically demonstrated a far greater benefit for deposition along lines which are aligned with the vehicle's direction of motion (Figure 8). This drag reduction is also economically favorable, with sizable "return on invested energy".[1]

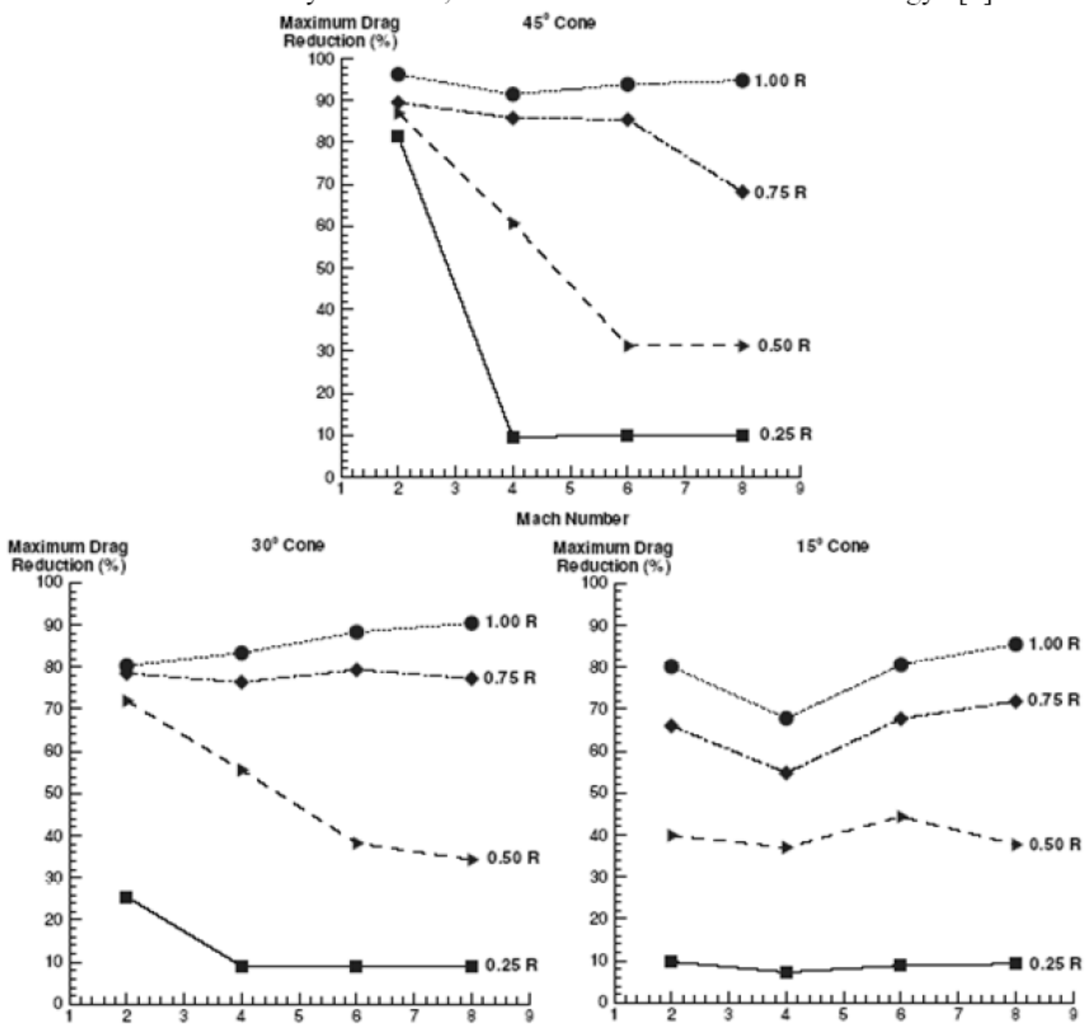


FIGURE 8: Display of the maximum drag reduction (percentage) resulting from the low density cores each of the supersonic flows computed. Bigger cores result in lower drag.

The effect directly benefits a number of hypersonic aerodynamic aspects, including:

- Eliminating over 90% of the drag
- Reducing surface temperature by 40-50%
- Affording control of a reusable launch vehicle by generating useful control forces and moments over its entire atmospheric flight path
- Allowing control authority over an otherwise unstable vehicle design
- Allowing much greater speeds at lower altitudes
- Reducing sonic boom
- Reducing fuel consumption
- Strong re-pressurization of the vehicle's base, significantly helping with propulsion.

To explore the control forces and moments associated with this technique, we used the Cobalt CFD solver to perform 3-D simulations, in which low-density cores were generated to impinge on the vehicle over a continuous range of off-axis positions. The offset in core position is depicted as upward in Figure 10. In these runs, the core's initial position was co-axial with the vehicle, and was then slowly moved upward (remaining parallel to the cone axis with no angle of attack). This allowed quasi-steady state assessment of the effects of the core, when offset by an amount ranging from co-axial to roughly one half of the base diameter. This is schematically depicted in Figure 9. We performed this series in order to explore the full range of responses resulting from cores aligned with the direction of flight.

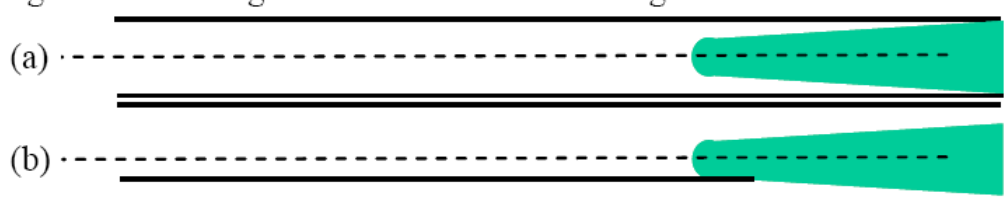


FIGURE 9: In the 3-D runs, the initial core position is axi-symmetric with the vehicle (a), yielding maximum drag-reduction and no lateral force or torque. The core is then gradually shifted upward as the run progresses, allowing a quasi-steady state value of control forces and torques to be monitored over this entire range of core positions. We characterized up to a shift of roughly 1/2 of the base radius (b).

Figure 10 depicts density, pressure and temperature on the body surface. The moments and torques are listed as coefficients on the same graph. The two moments are calculated as examples of different centers of mass that yield stable flight for different payloads/missions. We also demonstrated that otherwise unstable vehicles (center of mass aft of the center of pressure) are stabilized when flying through the low density cores.This is because the higher density gas at the outer edges of the base shifts the center of pressure significantly to the rear of the vehicle and behind the center of mass. This benefit of stabilizing otherwise unstable designs can result in far greater flexibility in ensuring stable hypersonic vehicles, removing conventional constraints on the location of the center of mass.

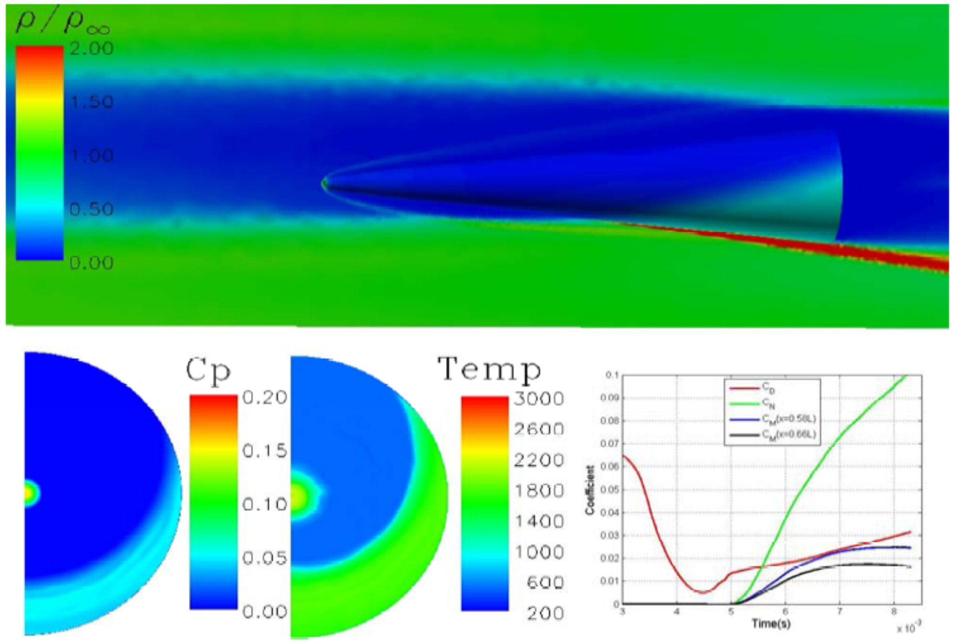


FIGURE 10: A frame of a test run using a standard cone to investigate the effects on heating, drag, and control forces when creating a hot low-density core ahead of a hypersonic vehicle's shock wave.

The analytical upper bound estimates and computed lower bounds on a generic cone yielded control forces from several G to many tens of G, depending on the altitude and Mach number. These upper and lower bounds provide helpful limits in assessing the utility of this technique in different applications. For a launch vehicle with a 1m base, we estimate that a deposited power of 480kW can produce a useful effect over the entire range of Mach 6-20. This power allows: 1/5 diameter cores to be opened ahead of the hypersonic vehicle at 15km; 1/2 diameter cores to be opened at 30km; and full-diameter cores to be opened at 45km altitude.

One of the most critical current needs in this field is mitigation of the thermal effects of sustained hypersonic flight. In addition to reducing drag and enabling vehicle-control, our approach also reduces the temperature on the vehicle surface, as well as the resulting heating, allowing significant reduction in TPS weights. Further weight and volume requirements can be traded when considering the hypersonic actuator/control surface systems we hope to obviate with our approach. Each flap has a sizable associated volume and weighs roughly 20kg. These actuators require either gas bottles or power from the vehicle, which have additional weight and volume demands, whose elimination can be used to offset the requirements for the energy-deposition system.

"GROUND TESTING" USING LASER ABLATION AND IMPULSE MEASUREMENT

In the absence of supersonic/hypersonic wind tunnel facilities, we investigated the effect of this technique on the spherical detonation wave generated by ablating a surface with a laser. In a vacuum, the ablatant escapes unimpeded from the target. In air, the high temperature gas is confined behind a shock wave in a high-pressure

bubble that pushes against the target (Figure 11). It is this geometry that we explored, not only for its effects on space launch/propulsion, but also as an opportunity to perform a small scale test of the effect of a hot core on a spherical shockwave. This shock geometry is different from that generated by supersonic/hypersonic vehicles, yet still represents an opportunity to measure the ability of a hot core to relieve pressure behind a shockwave.

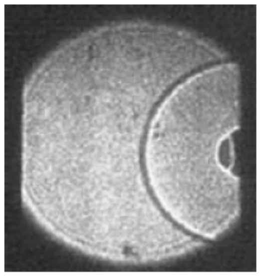


FIGURE 11: Shadowgraph image of shockwave from a nanosecond laser energy deposited in atmosphere on an Aluminum surface. Field of view, roughly 1.5".

In order to determine the gas-dynamic effects of a heated channel ahead of the ablated shockwave, we used two geometries, described below. These effects not only relate to thrust generation through laser-ablation in air, but also relate to the effectiveness of material removal in laser micromachining.

Low-Density Cores from an Ionized Beam Waist

In the experiments described below, we ablated a target mounted on a sensitive impulse detector. A reduction in impulse was taken to indicate a reduction in the pressure confined behind the shockwave, and an effective "puncturing" of the laser-ablation-induced shockwave. The first geometry we created to measure this effect is shown in Figure 12. In this study, we ionized the gas ahead of the target by coming

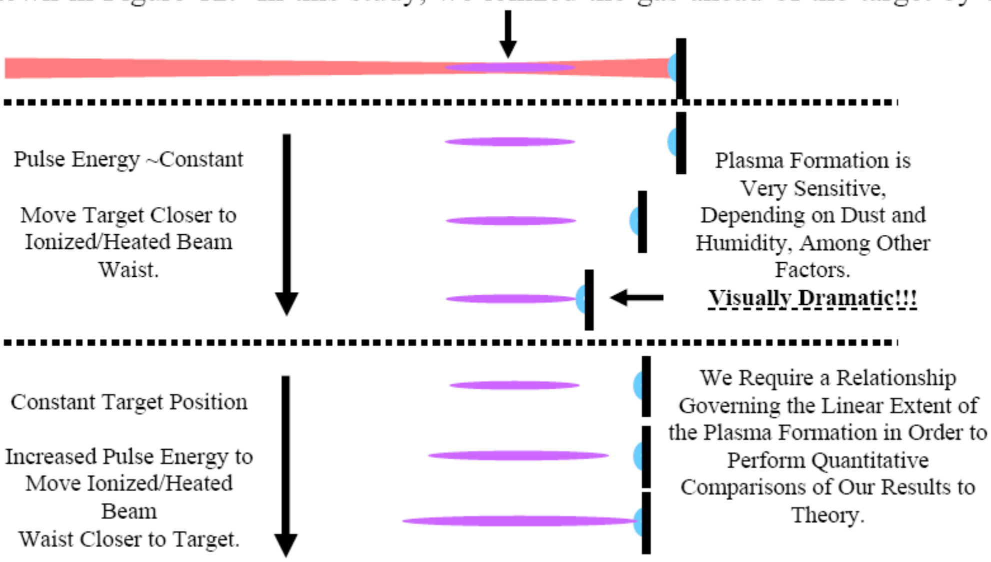


FIGURE 12: Two sets of measurements were performed to identify the effect of the heated core "connecting with" the shockwave from the laser-ablation. Top - using a roughly constant core length (roughly constant pulse energy), the target was moved toward the core. Bottom - keeping the target position constant, the core size was changed by varying the pulse energies.

to a focus before the target, resulting in an ionized beam waist (indicated by a downward arrow at the top of Figure 12). The position and length of the heated waist was a function of the pulse energy, and the target position could be moved forward or backward with respect to the position of the heated waist. These two parameters were adjusted to position the low-density channel, such that the hot ablated gas could escape along it, breaking its confinement behind the shockwave, reducing the pressure on the target, and yielding a reduced impulse imparted to the target. In the positions where the hot/ionized gases propagated along the hot channel, the signature was visibly dramatic. Instead of a confined flash at the target surface over roughly a 1/4" diameter half-sphere, the shockwave propagating into the heated channel resulted in a ~1/4"-diameter fiery plume extending forward 1-1.5" from the target (along the waist).

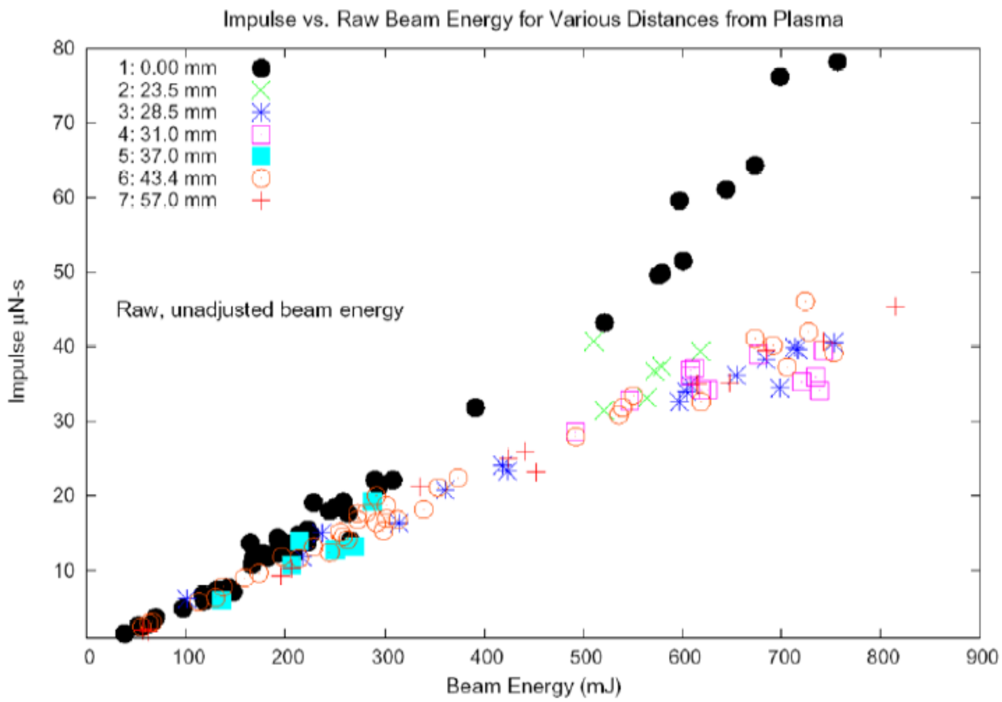


FIGURE 13: Impulse vs. Beam Energy, as measured on a target located at different positions with respect to the beam waist. 0.0 is the only measured position in front of the beam waist.

The impulse we measured at different target positions in the ablation geometry of Figure 12 is shown in Figure 13. The 0.0mm position is in front of the region of heated focus and did not suffer losses due to ionization in the air. The data in Figure 14 is the data in Figure 13 for positions other than 0.0mm, after the energy illuminating the target was adjusted (through an earlier calibration) to account for the pulse energy lost in creating the ionized beam waist. These data points effectively fall on the same *impulse vs. energy* curve as the data points measured at the 0.0mm position ahead of the ionized waist, exhibiting variations due to the shock/core interactions.

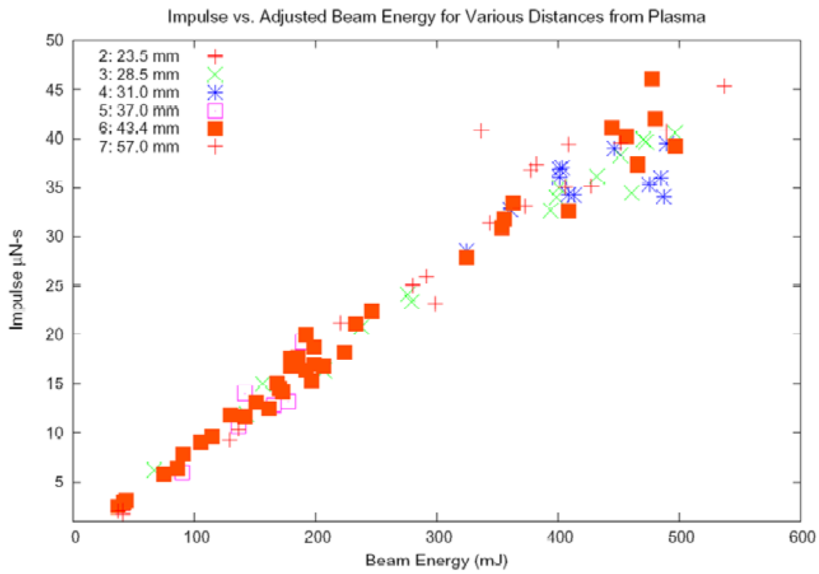


FIGURE 14: Data of **FIGURE 13**, measured after the ionized beam waist, calibrated to adjust for the energy lost in traversing the beam waist, so that energy "on target" is shown in the graph.

The dips in impulse, corresponding to the visually dramatic channeling of hot gases along the low-density core, are better illustrated in Figure 15. In Figure 15, the data of Figure 14 is plotted over the energy range, within which the plume was visually observed to most effectively channel along the low-density core/waist.

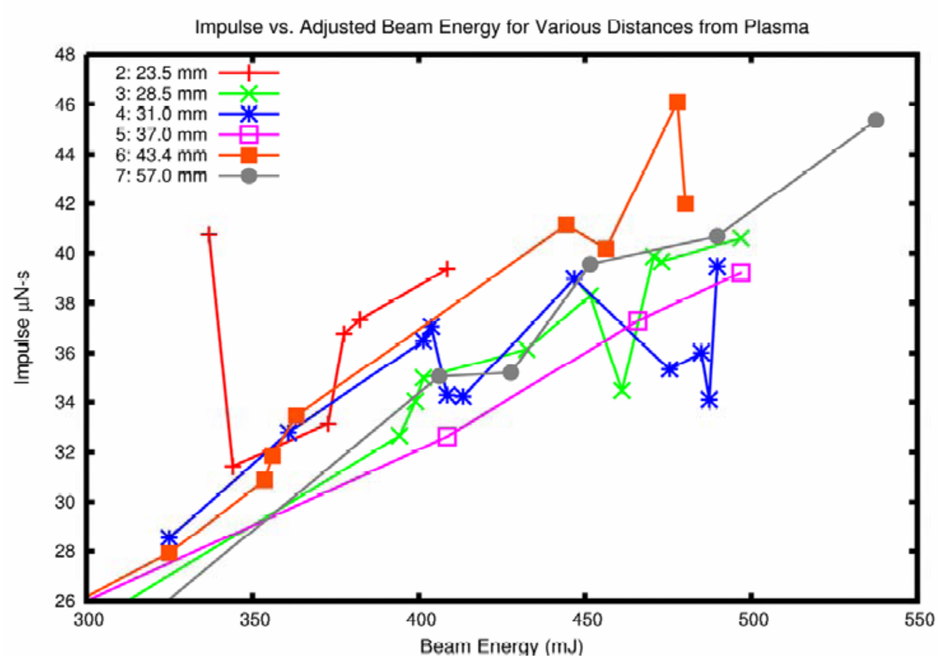


FIGURE 15: The data of **FIGURE 14** over the energy-range exhibiting the impulse dips corresponding to the hot ablation products channeling along the low-density core, away from the target.

The measurements shown in Figure 15 demonstrate a reduction in impulse on the order of 15-20% for the three effective combinations of target position and pulse energy (corresponding to waist length) as shown in Table 1:

TABLE 1 Pulse energy and target position demonstrating reduced impulse from **FIGURE 15**

Target Position	Pulse Energy Corresponding to Pulse Dip
23.5mm	375mJ
28.5mm	460mJ
31.0mm	480mJ

The corresponding differences between these three data combinations in target position and pulse energy (with the corresponding difference in core length) are shown in Table 2:

TABLE 2 Differences between Data Combinations

Δx (target position)	ΔE (determines length of low-density core)
5mm	85mJ
2.5mm	20mJ

Low-Density Cores from Filaments

The second geometry we generated to create hot, low-density cores to channel high pressure gas from behind the shockwave (i.e. to puncture the shockwave due to ablation), was to hit the target with filamenting laser pulses (Figure 16). These laser pulses showed very little ablation over the spot diameter, except at the high-intensity regions of the filaments (each roughly 100-200μm in diameter).

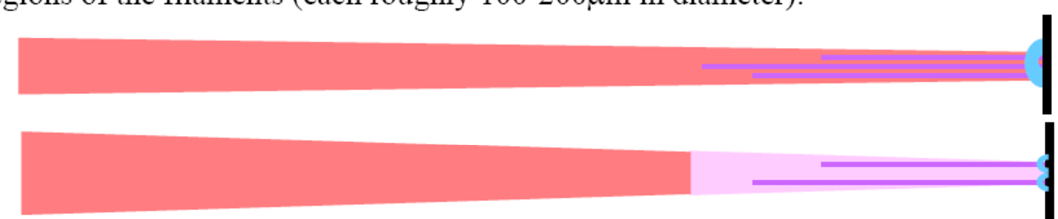


FIGURE 16: Schematic diagram of potential shock wave geometries that can result from the interaction of filamenting laser pulses with a target.

Ultrashort laser pulses were propagated toward the targets under conditions suitable for filaments to form. With higher energy pulses, more filaments were observed. One can argue that as the filaments become more energetic/intense, the hot channel they create allows more of the high pressure gas to escape from behind the shockwave and thereby reduce the coupling constant of higher intensity/fluence filaments. The dynamics include effects of both ablation efficiency and aerodynamics, and an accurate explanation of this effect requires more investigation.

CONCLUSION

Depositing energy along a line ahead of a supersonic/hypersonic vehicle stands to solve a number of the outstanding problems in high-speed flight. In particular, depositing the energy along the stagnation line results in elimination of more than 90% of the drag in many cases, and the reduction of surface temperatures by 40-50%. Depositing the line of energy at a slight angle, or slightly off-set from the stagnation line furthermore yields sizeable steering forces and moments over the entire atmospheric flight envelope. The investigated geometry opens a low-density core along the line, allowing the vehicle to fly through it with very little resistance.

Another way of viewing this is that the high pressure gas confined behind the shockwave is being allowed to escape forward along the low-density core. A third perspective is to consider the effective Mach number of the vehicle to be greatly diminished (potentially subsonic), thereby greatly reducing the drag. In addition to the streamlining effect on arbitrary bodies, we observe that this geometry is capable of stabilizing vehicles that are otherwise inherently unstable. In a separate study, the effect was demonstrated to be energy efficient, in that depositing a certain amount of energy ahead of the vehicle saves a much greater amount of propulsive energy than that deposited upstream. The physical intuition behind this is that the deposited energy goes completely to moving the gas ahead of the vehicle just to the side of the vehicle, in principal adding no more kinetic energy to the flow than necessary. In contrast, not moving the gas out of the way of the vehicle, results in the air being accelerated to speeds comparable to those of the vehicle, leading to a great deal of wasted energy. An analogy is that of the energy required by a snow plow to drive through snow at a high speed while accelerating snow forward and to the side. The proposed technique amounts to shoveling snow just to the side of the road and allowing the snow plow to drive without resistance and without imparting any lasting/excess kinetic energy to the snow. In the aerodynamic case, this high density gas sitting on the "edge of the road" is recirculated behind the vehicle to repressurize the base, pushing the vehicle forward and providing a much higher density against which a propulsion unit can push. In the case of the core being smaller than the vehicle base, there is still an advantage, analogous to a projectile penetrating a continuous medium versus penetrating a medium with a hollow path already provided, facilitating penetration and guidance. In addition to our simulations and analytical work, we performed laser ablation experiments that demonstrate the ablation shockwave being punctured by a low-density core created from energy deposition in the air, thereby reducing the impulse imparted to the target.

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